NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

No. 1083

MICROMECHANICAL STUDY OF METALS

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First Communications of the New International Association
for the Testing of Materials

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The Institut Scientifique Expérimental des Transports at Moscow established toward the end of 1925 had since its inception included in its program the study of the mechanism of plastic deformation and the problems associated with it with reference to the materials of the means of transport. Before the program thus determined upon could be carried out, it was necessary to adopt a method of research, or, more exactly, a system of such methods. Because of the modest equipment of the laboratory of the recently established institute, the choice of any particular method was determined not only by the advantages it offered but also by the resources available. As a result of a series of studies and investigations, a method was determined upon which in this paper will be denoted as the "micromechanical" method.

The underlying basis of this method is already known. As will be seen from the description that follows, the micromechanical method is merely a combination of the micrographic study of plastic deformations with mechanical tests on small specimens. It is a well-known fact that a number of investigators have largely employed and still are employing these two procedures and have thereby obtained good results. The authors of the present paper have found it useful to combine the two methods by making the two studies simultaneously on the same specimen.

The observation of the development of the deformation lines on a polished and etched specimen has largely been utilized in studies dealing with the phenomenon of plastic deformation but very little as an investigation procedure of the properties of each individual structure. The observations made in the course of the present investigation show that the process of the development of the microdeformations often includes complementary characteristics with regard to the properties of the structure of the metal under examination and therefore should be of particular interest. The mechanical study of specimens of small dimensions, which forms the second, integrating, part of the micromechanical method, offers the natural advantage: namely, that the small dimensions

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*"Etude Micro-mécanique des Métaux." First Communications of the New International Association for the Testing of Materials, pp. 328-338.

of the specimen permit the specimen to be taken from any part of the body
to be tested and in different directions. This gives a means for study-
ing the materials at different points. It is seen from figure 1 that the
specimens used still are too large in comparison with those used by many
other investigators but are nevertheless sufficiently small for the prac-
tical purpose for which they were intended.

The tests on the specimens for resistance to compression were car-
ried out by means of the machine of Gagarine; while the tests on the re-
sistance to tension were conducted on a special apparatus built by
Lorenz. (For the description of the apparatus, see reference 1.) The
Lorenz apparatus permitted stressing the specimen to the breaking point
on the microscope stand itself. It is thus possible to observe in con-
tinuous fashion a certain group of grains during the entire stressing
process - that is, up to the instant of failure - or to examine micro-
scopically, at each stage of the deformation, the entire specimen under
tension.

Two types of specimen were employed for the tension tests, the
first type without a notch (fig. 1a) and the second type with a notch
(fig. 1b). In choosing a certain group of grains in a specimen of type
1a to make a continuous examination of it, it was only by chance that a
group was discovered which was at the limits of the constriction formed
toward the end of the test. In most cases the group chosen was outside
the constriction; that is, where the last degrees of the deformation
leading to the break did not present themselves. The notched specimens
(fig. 1b) on the contrary permitted observation of the grains which in-
variably fall within the region near the strongest deformations. The
presence of a notch, however, results in a great complexity in the dis-
tribution of the tensions and distorts the entire character of the phe-
nomenon. A complete examination of the specimen at a certain period of
the deformation has remedied somewhat the defects of the two types of
specimen by permitting the study on an unnotched specimen of the zones
of large deformation and on a notched specimen the zones removed from
the failure section that have a less intense distribution of the defor-
mations.

The specimens were polished and etched before the test. For mild
steel the etching was stronger than the usual one for revealing the
structure of the metal in order to bring out better the contours of the
ferrite grains, since the deformation lines in a metal with little car-
bon are concentrated principally in the ferrite while the pearlite re-
mains intact. With the object of studying the change in the shape of
the surface of the grains, the successive phases of the deformation were
fixed by tracing on mat glass, in addition to taking photographs.

In order that the results to be expected from the application of the
micromechanical method may be judged, the discussion is given below of

several results on three different characteristic structures: namely,
mild steel used in the construction of bridges, nontreated rail steel,
and finely granulated chrome and nickel steel. In the present paper,
the numerical results of the mechanical tests are not given, the numer-
ical figures having only a relative value since the mechanical proper-
ties of any specimen depend on its shape and dimensions. The readings
obtained in these tests can be used only as comparison values. It is
believed that it would be impossible in practice to give the coeffi-
cients relating the small specimens to the normal specimens, because a
normal specimen gives a mean value of the mechanical properties of some
definite part of a body while a small specimen characterizes the metal
only in a reduced zone. In the present paper will be given the micro-
graphical characteristics of the three substances mentioned above with
respect to the development of the permanent deformations which are pro-
duced.

In the mild steel, as also in the other materials studied which on
the tension diagram present a well pronounced curve, the first visible
lines of deformation appear at the end of the curve. Up to that time,
the change in the shape of the grains is produced probably by slip of a
magnitude below the resolving power of the microscope. The first lines
of deformation appear most often in a group of grains of similar orien-
tation (fig. 2). The resistance to slip on the contour of the grains
being weakened in the case where the slip appears in these places rather
than elsewhere and the corresponding lines pass in a continuous manner
through a series of grains of practically coinciding orientation. The
slip bands then arise relatively rapidly in the grains of a size consid-
erably exceeding the mean dimensions or in grains of a very irregular
shape. On the other hand, certain grains with boundaries similar to
those of a regular polygon and having dimensions below the mean, remain
at times quite intact even at the stricture itself. The directions of
the lines of deformation ordinarily form an angle limited by the normal
and an angle of 45° with the direction of the tension. Lines parallel
to the direction of the force are almost completely absent.

As the deformations increase, deformation lines arise also in the
new grains. As has been said, the orientation of these lines with re-
spect to the direction of the axis of the force remains the same. In
the grains already deformed, there is noted the appearance of new lines
as well as the increase in length and width of the old lines. Generally,
at the beginning the lines of deformation start at an extremity of the
grain and do not cross it entirely. Lines also have been observed that
form at the middle of the grain and at first do not reach any of the ex-
tremities.

It is believed that there are as yet no tests establishing, in an
irrefutable manner, whether these lines are slip lines or microscopic

fissures. It is certain that even if the lines which are observed at the beginning are lines of perceptible slip they degenerate into fissures in a relatively short time. Evidently, it would be of great interest to determine the transition from the slip to the fissure and the tension corresponding to this state. This value would represent an important characteristic of the material. The following conventional procedure for dividing the deformation lines into three categories has been determined. As belonging to the first category are considered the lines which disappear on the repolishing of the specimen and do not reappear after re-etching. As lines of the second category are those which arise after the re-etching but which then disappear after the annealing. Those lines, which remain after the annealing belong to the third category. It is to be noted that this classification requires a greater precision, and yet to be fixed are the degree of polishing and of etching, the temperature and the duration of the annealing, and the medium in which the annealing is carried out.

At the highest degrees of deformation, the lines are unquestionably those of fissures. They even cease to be approximately parallel as they are at the beginning of the deformation, but bend and intercross and at times even take the shape of a fork. The number of lines in each grain is high only in exceptional cases. In a nonannealed metal it is relatively rare that the grain is covered by a large number of lines. For example, a grain under a compressive force such as is shown in figure 3 is an exception.

A system of intercrossed deformation lines is only rarely observed in the tensile state, the exceptions appearing only at the stricture. The system of intercrossed slips is typical, however, of compression (fig. 4). There is readily observed during all the phases of the deformation the effect of the resistance to slipping on the contours of the grains, a resistance which is due to a different orientation of the single grains and more still to the presence at the boundaries of the grain of a harder crystalline constituent. The plane figure which is examined under the microscope gives only an insufficient picture of the spatial phenomena to which the deformation phenomena belong.

A second example of the application of the micromechanical method is, as has been said, to the study of the rail metal. The investigations undertaken by the Institut Scientifique Expérimental des Transports are in connection with a large project undertaken in the Soviet Union by a special commission, with the object of studying the rail problem. Rails removed from the road have been used for the micromechanical specimens and investigations of the above-mentioned commission. Among these rails there were some that have proved themselves to be of good quality and others that were defective. The results obtained from the specimens taken from the upper, hence most fatigued, part of the rail differed appreciably from those obtained on specimens taken from other parts of the

same rail. The specimens taken from the upper part of the rail fail before any important visible marks of deformation have been able to develop.

The phenomenon to be mentioned next is the first apparent index of the deformation, an index which can be estimated only subjectively and cannot be fixed in a quantitative manner. As soon as the elastic limit is exceeded, the pattern of the pearlite is greatly accentuated under the naked eye and the entire structure marks a great contrast. It is to be observed that toward the end of the test the boundaries and the appearance of the grains again become less distinct. This probably is due to the fact that the polished surface ceases to be plane. This phenomenon is visible on all the photographs reproduced, and the result is that at the stages of advanced deformation it was found necessary to use only a single section of the visible field, the remainder generally being out of focus.

The first lines of deformation, particularly for the unnotched specimens, are ordinarily visible in the ferrite (fig. 5). Sometimes these lines attain a considerable development and evident fissures appear in the ferrite without any lines of deformation being formed in the surrounding pearlite (fig. 6). The phases of the more advanced deformation as well as the initial phases near the notch also reach the pearlite where deformation lines are observed along and across the lamellas. The deformation lines crossing the pearlite penetrate and generally also cross the neighboring grains of ferrite which offer no resistance to the propagation of the deformation over their boundaries. These lines stop only at a grain of pearlite succeeding the ferrite, as is seen in figures 7 and 8, which represent the same point of the specimen differently magnified and at a different angle of incidence of the light. In the specimens from the external surface of a rail taken from the road deformation lines of a special appearance were found after their failure (figs. 9 and 10). It was not possible to observe under the microscope the precise instant at which these fissures occurred. Such fissures were not observed on a nondeformed specimen. In studying these lines under a different angle of incidence of light, they could still be observed for nonmetallic particles.

Chrome and nickel steel of the following composition presents a third example of the application of the method being described:

C . . . 0.40   S . . . 0.01   Ni . . . 3.52

Si . . . 0.14   P . . . 0.03

Mn . . . 0.54   Cr. . . 1.02

The mechanical properties of this metal may be characterized by the following results obtained from normal specimens:

Tension . . . . kg/mm² . . 59.5

Extension . . . . percent . . 18.1

Although these figures indicate a considerable plasticity of the metal owing to its finely granulated structure, it was not possible to make out any visible marks of deformation of the surface of the sample. The general appearance of a specimen at a point taken outside of the constriction is shown in figure 11. As may be observed on this photograph, a milder crystalline constituent presents a series of slip bands. As for the constriction itself, it is to be observed that because of the deformation in the plane of the surface of the specimen, so that the surface itself ceases to be plane, the pattern of the structure becomes so indistinct that it is difficult to recognize the old character of the nondeformed metal. The photograph (fig. 12) shows, to a very large magnification, a point of the specimen near the constriction at the phase immediately preceding the failure.

At the time the present paper was being prepared, the authors already had made some observations on the effect of a preliminary deformation of the metal from which the specimens were prepared. There exists a typical difference between the appearance of the deformations of a specimen of this kind and of a specimen of a metal which has not been subjected to a force. The lines of deformation in the metal previously subjected to a compressive stress have along the axis of the specimen an orientation near the normal, while in the case of the nonstressed metal the predominant orientation of the lines of deformation makes with the axis of the specimen an angle of approximately 45°. A second indication of preliminary compression is the presence of grains forming a system of intercrossing slips, a phenomenon rarely observed on a specimen without preliminary compression.

The slip bands in the grains having two systems of deformation are generally less curved and less spaced between them than is the case in the other grains. In the same grain can be observed intercrossed slip bands (fig. 13) as well as systems of bands of double slip. The grain which is at the center of the photograph (fig. 14) is a characteristic example of a deformation of this kind. The different parts of this grain are traversed by slips or fissures which are merely a prolongation of the deformation lines of the neighboring grains adjacent to the parts of the grain under consideration. The number of observations on the alternated deformation (compression-tension) which had been made at the time the present paper was written was not sufficient for any conclusions to be drawn.

The results already obtained encourage the Institut Scientifique Expérimental des Transports to extend the investigations to the study

of combined plastic deformation: that is, the phenomena of compression, longitudinal and transverse tension, torsion, and so forth. The Institut intends in the near future to conduct research on the phenomenon of "aging" in a state of tension and, finally, on the effect of a dynamic load on the plastic deformation.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

REFERENCE

1. Velikov, P. A., and Stchapov, N. P.: Étude expérimentale sur les Déformations plastiques. Revue de Métallurgie, 1929.
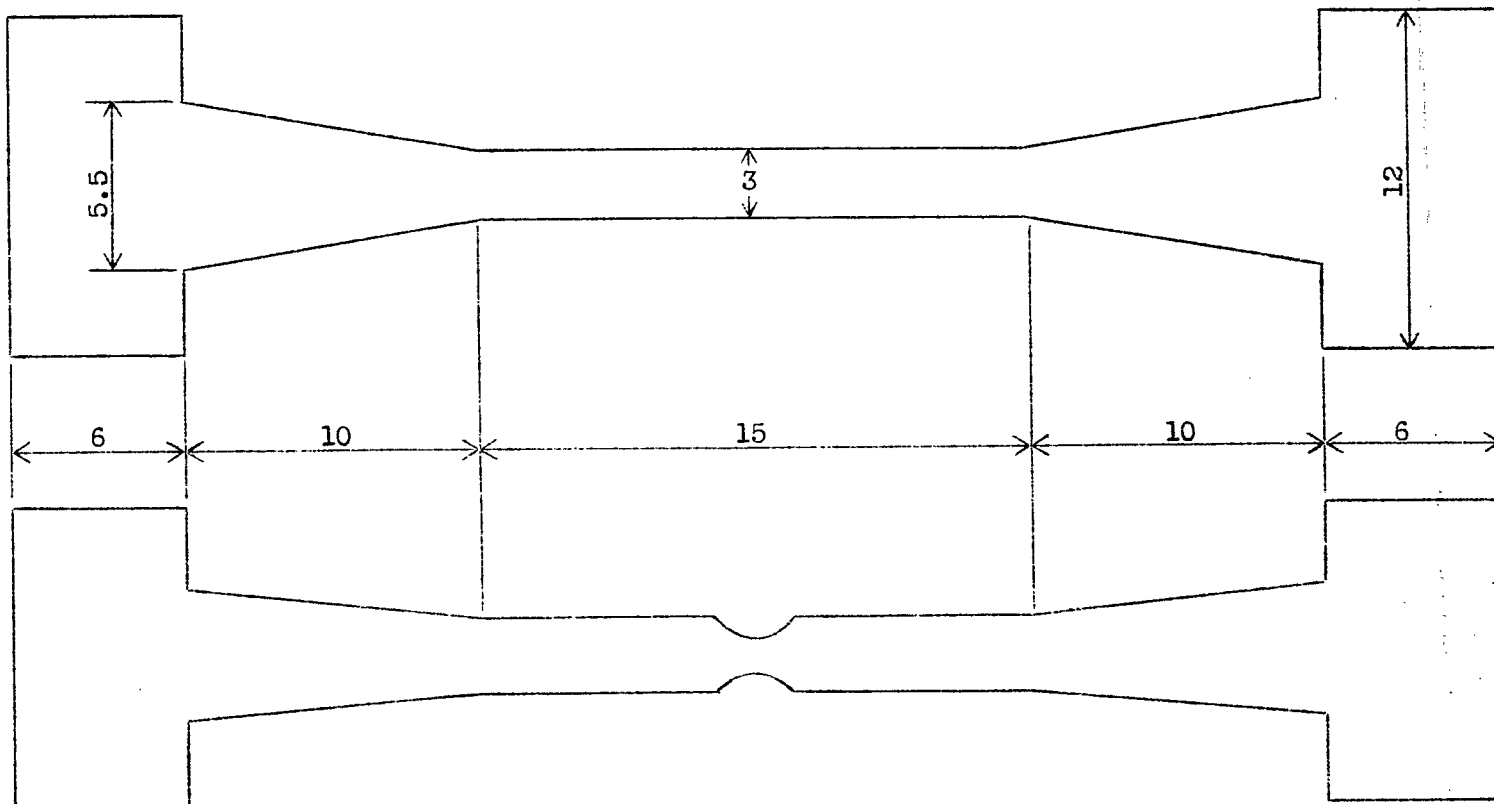
Figure 1.

Fig. 1
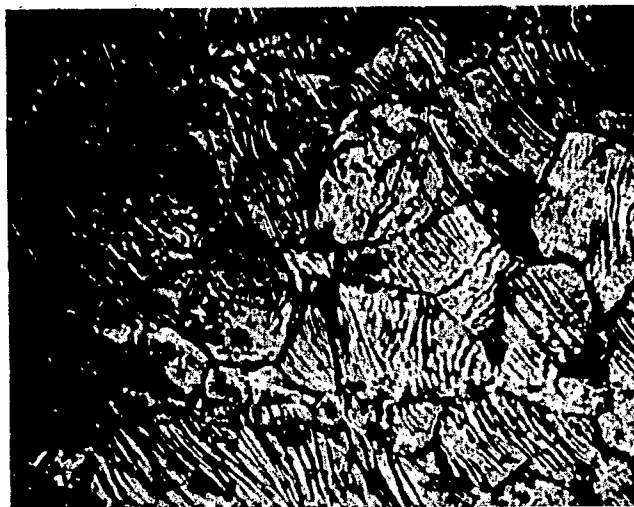
Figure 2.
Magnification 660

Figure 3.
Magnification 1260
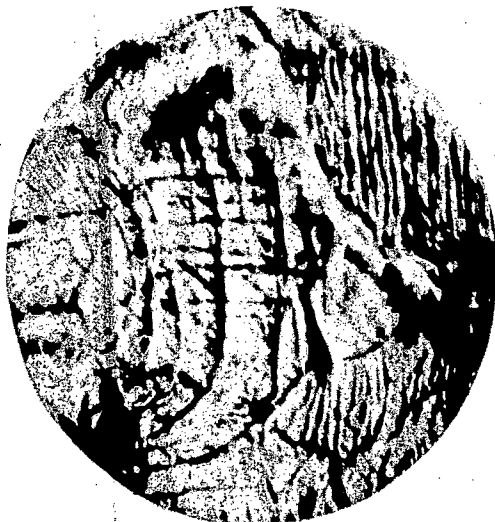
Figure 4.
Magnification 1260

Figure 5.
Magnification 700
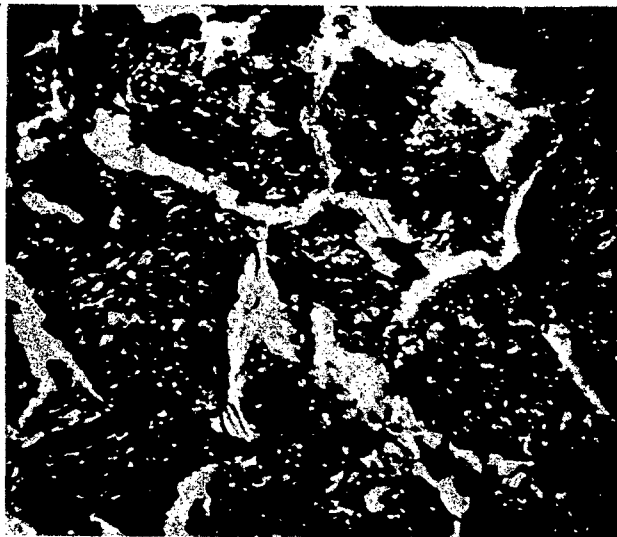
Figure 6.
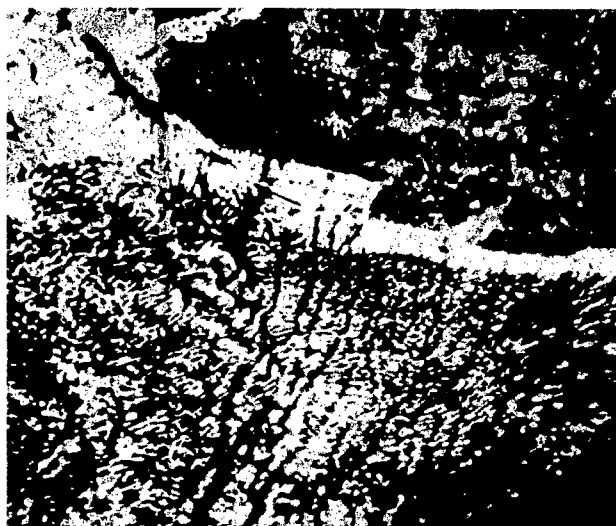Magnification 660

Figure 7.
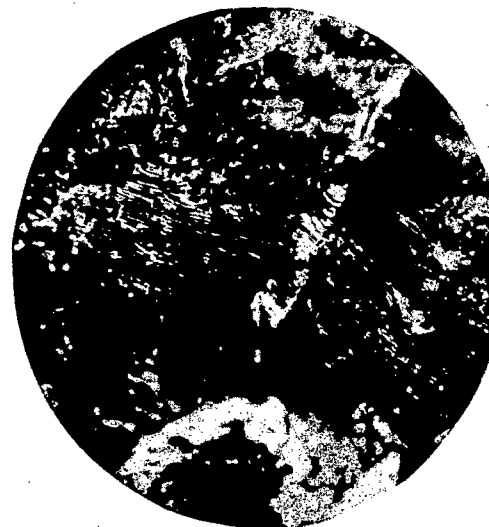Magnification 660

Figure 8.
Magnification 1260

Figure 9.
Magnification 660

Figure 10.
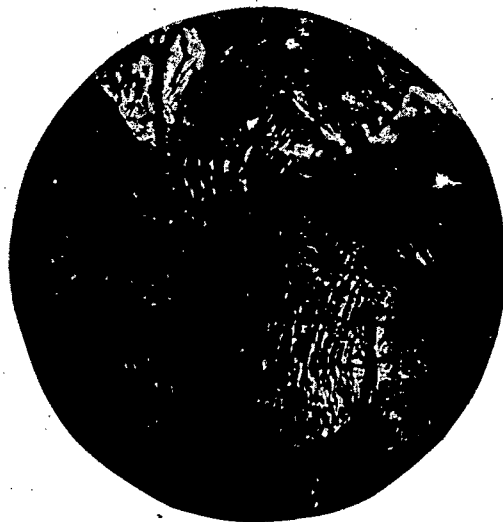Magnification 660

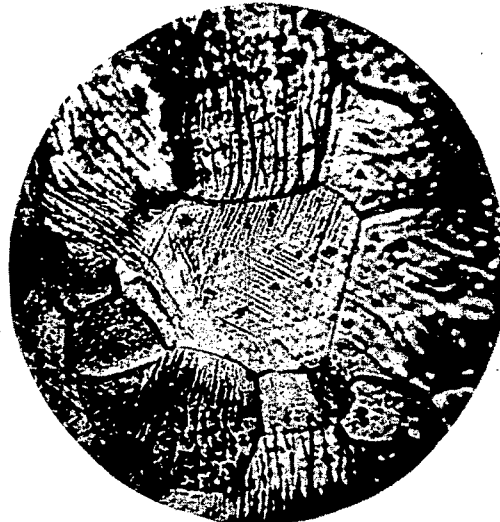Figure 11.
Magnification 330

Figure 12.
Magnification 1360

Figure 13.
Magnification 660

Figure 14.
Magnification 660

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Authors ③

Metals - Plasticity
Metals - Tension Tests
Metals - Compression tests
Metals - Strength, Tensile
Metals - Elasticity
Metals - Fatigue tests
Metals - Tension tests, Notched
Metals - Crystallization
Instruments - Microscopes
Inspection - Metals
Steels